QUARTERLY PROGRESS REPORT NO. 3

CRACK INITIATION IN METALLIC MATERIALS

FOR

Department of the Navy
Bureau of Naval Weapons
Washington 25, D. C.

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Metallurgical Research Laboratories
Department of Chemical Engineering and Metallurgy
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by

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Abstract

The theoretical analysis of hole and notch stress fields has been continued. It is shown how the maximum stress of an elliptical crack is orientation dependent.

The experimental investigation on the effect of surface defects has been continued. Notched sheet specimens of Ti-2.5Al-16V, heat treated to an extremely brittle condition, have been tested in uniaxial tension. One set of these specimens contained an additional "piggy back" notch which had been produced by scratching with a needle before and after heat treatment aging.

Analysis of the data is not yet completed.

To study the effects of surface condition on the fracture strength of tungsten,bend tests (in three point loading) where conducted on machined specimens from which various amounts of surface material had been removed by electropolishing. As-received material showed a marked improvement with increased surface removal while recrystallized material showed a loss in strength for surface removal up to 0.010 in.

Theoretical Considerations

a. Effect of Crack Orientation

The previous Quarterly Progress Report No. 2 gave a calculation of the tangential stress distribution at the surface of an elliptical hole.

The maximum stress should be found where

$$\frac{d\sigma}{dV}\bigg|_{\alpha=\alpha_0} = 0$$ (Equation 12, Quart. Prog. Rep. 2)

(σ = stress, V = coordinate in elliptical system, $\alpha = \pi/2 - V$)

from which followed that

$$\alpha_0 = \sqrt{\rho/t} \times 0.72$$ (Equation 13, Quart. Prog. Rep. 2)

It follows that at the ellipse (for definitions see Fi. 3, p. 12 of Appendix, Quart. Prog. Rep. 2, 1963)

$$tg\,\beta = \frac{dx}{dy}\bigg|_{\alpha=\alpha_0} = \left(\sqrt{1+(\cot\gamma)/3} - (\cot\gamma)/3\right)^{-1}$$

The results of a numerical calculation of the direction of maximum stress at the tip of an elipse is given in Fig. 1.

b. Effect of Notch Surface Preparation

The effects of various notch surface conditions on the room temperature notch strength of recrystallized tungsten were reported previously. (Quart. Prog. Rep. 2). Accordingly, for a constant theoretical stress concentration factor the "machined and electropolished" specimens reached a higher notch strength than the "machined specimens" which again were stronger than the "electropolished" specimens. It is suggested that this seemingly paradoxical behavior can be explained with the previously proposed model of the superposition of various surface defects. The dislocation density of recrystallized tungsten is rather low and the material is consequently very brittle. Machining the surface should produce an increase in the dislocation density, increasing therefore also the amount of possible microplasticity and fracture strength.

At the same time microcracks may be produced which should decrease the fracture strength. The former effect seems to be dominant for the present case since machined specimens had a higher fracture strength than electropolished specimens. If a machined specimen is then electropolished, some of the cracks disappear or are smoothed out. This should further increase the fracture strength. However, since the machining causes a varying dislocation density with a maximum just below the surface, surface removal also decreases the dislocation density at the surface. That means that after prolonged surface removal the same condition as in only electropolished recrystallized specimens (with a lower fracture strength) should be obtained.

Experimental Results

a. Tungsten Bend Tests

Two series of bend specimens have been designed and tested in an attempt to study the effects of surface condition on the bend strength of recrystallized and as-received tungsten. The three point bend specimens are shown in Fig. 2. The tension surface was ground in the direction perpendicular to the major stress direction, closely approximating the type of surface obtained at the root of a notch after machining. A photograph of the ground surface is shown in Fig. 3A (50X). Half of the specimens were recrystallized, the rest remained in the as-received condition. The surface of the specimens were then electropolished to the various depths to remove varying amounts of the surface gringing marks (Fig. 3B, C and D). They were then tested to failure in bending with the previously ground surface as the tension face.

The experimental results are shown in Fig. 4. The strength of the as-received material increased as the amount of surface material removed increased. This agreed qualitatively with results obtained previously. The electropolished surface was stronger than the machined surface. The recrystallized material shows first a rapid decrease and then a slow increase in strength as more surface material is removed. The appearance of the tension surface of these specimens show that the electrolytic process removes initially many of the shallow scratches, leaving widely separated deeper scratches, (Fig. 3A and B,) then slowly rounds off the surface to remove these marks (Fig. 3C and D).

An analysis of these data has to take into account both the geometric changes of the surface and the changes in characteristics of the material near the surface. The recrystallized material has a low dislocation density and is therefore very brittle. The specimens tested in the as-received condition should show microplasticity due to a higher dislocation density. Both types of specimens should have initially the same geometric surface structure.

For both series the fracture strength increases nearly linearly with amount of surface removal, except for the first 0.010 in. This increase in fracture strength is expected because the surface becomes much smoother with prolonged polishing. However, at the beginning of the electropolishing, either the fracture strength increases less rapidly than in the linear stage in the specimens tested in the as-received condition, or even drops below the initial fracture strength in the recrystallized specimens. During this initial electropolishing only exposed tips and ridges should be removed. That should not effect the stress distribution at the root of the grooves. Therefore, it

should be concluded that a secondary effect is responsible for the initial reduction in fracture strength. One possibility is a change in surface energy due to wetting by the electrolyte. One would expect a more pronounced effect at recrystallized specimens, because they have cleaner surfaces due to the heat treatment in vacuum.

b. Tungsten Transition Temperature Studies

Several tensile tests at elevated temperatures were made to determine the temperature of the ductile to brittle transition temperature of the as-received tungsten. There was no visible plastic flow in specimens tested at room temperature. At 300°C some plastic range can be seen in the stress strain curve Fig. 4. The plastic strain increases with increasing temperature i.e. 400° and 500°C. The tests at 500° showed a large drop in strength prior to fracture and a large amount of necking. The reduction of area as a function of test temperature is given below:

	RA
RT	0
200°C	10%
300°C	17%
400°C	19%
500°C	95%

These tests will be repeated with recrystallized tungsten specimens to determine their transition temperature.

c. Brittle Titanium

It has been proposed previously that a calculation of the stresses in metals has to take into account that usually several stress fields have to be superimposed. The SCF should be found by multiplying the SCF of the specimen geometry, surface scratches due to machining and surface steps due to slip grain boundary steps, etc. A calculation of the SCF is only possible for a few simple systems such as for elliptical holes. It was therefore decided to obtain experimental data on the effect of superimposed stress fields and specimen preparation.

Series 1

Several double notched specimens as previously described in Quart. Prog. Rep. No. 2, have been made and tested. Notches with a depth of about 30% were produced by machining the specimen in the solution treated condition, followed by a short electrolytic cleaning. The root radius varied to give K_t values from 1.5 to 3.2. Some of the specimens were scratched with a diamond indenter to produce "piggy back" notches with a radius of about 0.001" and a depth of about 0.0015" at the root of the primary notch. The brittle titanium alloy was used because of its relative ease of machining in the solution treated condition.

Three series were tested as follows:

Series 1a - Secondary notches scratched into the specimen with diamond indenter after heat treatment for maximum brittleness.

Series 1b - Secondary notches scratched into the specimen with diamond indenter before the heat treatment for maximum brittleness

Series 1c - Specimens without secondary notches, tested after heat treatment

The results of these three series are shown in Fig. 5. In addition, prior data obtained on a different heat of this alloy is plotted for comparison. All the results obtained in this study yield maximum stress values higher than those obtained previously. From the data the theoretical curve $\sigma_N K_t = \sigma_{max}$ appears to be obeyed for Series 1a and 1c from the limited range of K_t used. Deviation from the 45° line can be seen for K_t = 1.5 for a specimen of series 1b.

The lowest strength was obtained with Series 1a (secondary notch after heat treatment) with an average decrease of about 40 KSI or the equivalent of an increase in K_t by about 1.2 from values obtained in Series 1c.

It is surprising to find only a small decrease in strength due to surface scratches. This may be due to a different surface structure in scratched or machined specimens. It indicates why results from different series cannot be correlated with each other directly. It is interesting that the slope of Series 1b is much smaller than 45°. Usually one observes an angle of 45° for perfectly brittle material, and less than 45° for microplasticity, which is normally explained with the occurrence of microplasticity but it can also be due to the "piggy back" effect. It has been shown that the stress gradient at the root of a notch is inversely proportional to the notch radius.

We should therefore expect if we plot the log σ_F versus log K'_t (K'_t is the SCF of the notch only) that the actual fracture stress of the specimen with "piggy back" notches σ_F is below the values for the fracture stress of the specimens with only the machined notches, σ'_F. Therefore $\sigma'_F - \sigma_F$ should have its largest value for $K'_t = 1$ and should become zero for $K'_t \rightarrow \infty$. The SCF of the "piggy back" scratch K'_t could be determined from the extrapolated difference of $\sigma'_F - \sigma_F$ at $K'_t = 1$.

d. Tests of Specimens with Machined "Piggy Back" Notches

Results of some preliminary tests of(Ti-2.5Al-16V) specimens heat treated for maximum brittleness at 700° for 4 hours are given in Table I.

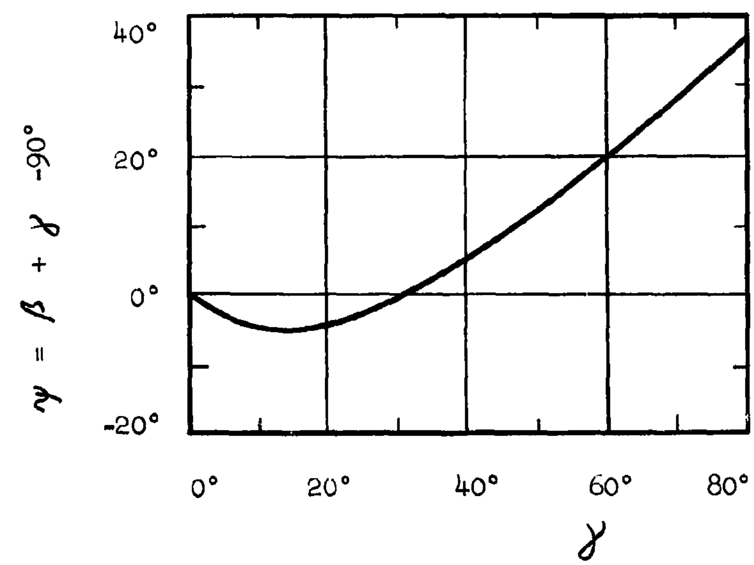


FIG. 1 ANGLE BETWEEN DIRECTION OF MAXIMUM STRESS AT THE TIP OF A THIN ELIPTICAL HOLE AND THE LOAD DIRECTION (FOR DEFINITION OF ψ, β, AND γ SEE QUART. PROG. REP. NO. 2, p. 13)

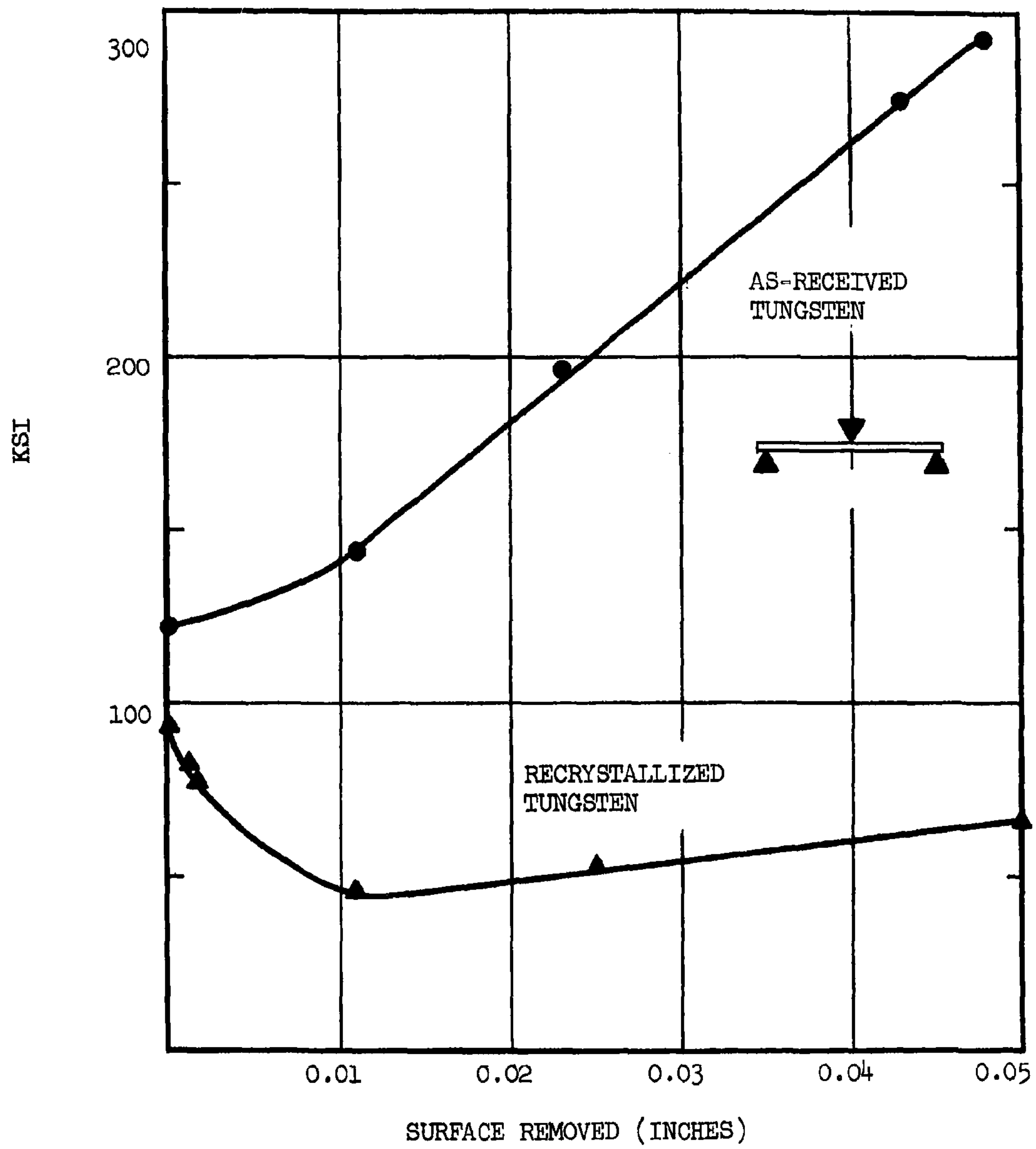
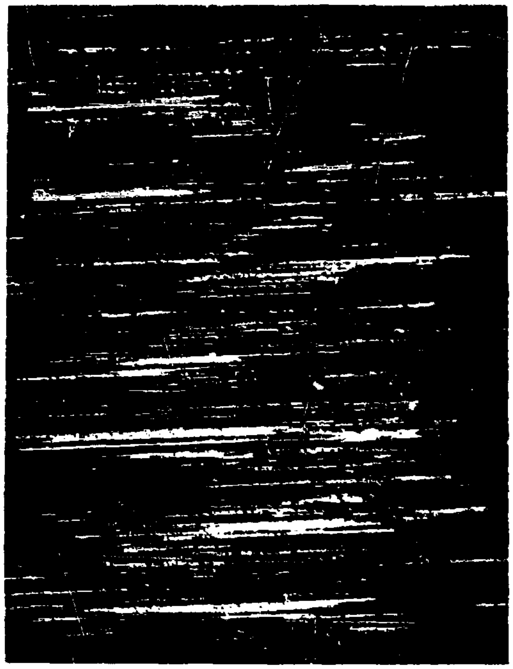
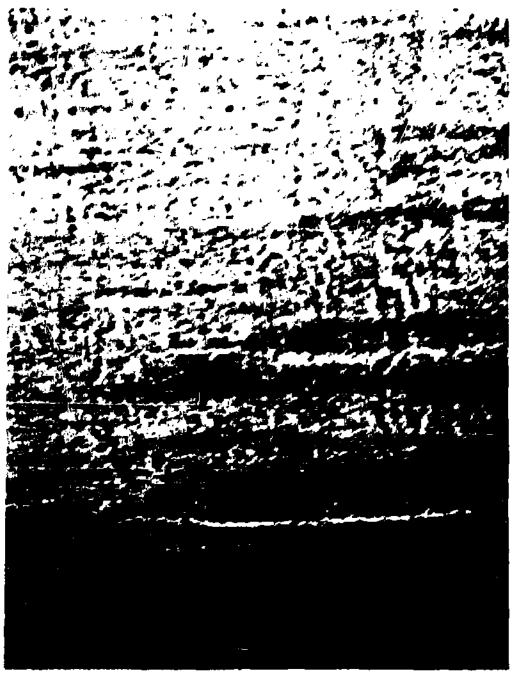


FIG. 2 EFFECT OF ELECTROPOLISHING FOR VARIOUS TIMES ON THE BEND STRENGTH OF TUNGSTEN. ORIGINAL WIDTH OF SPECIMENS .125".

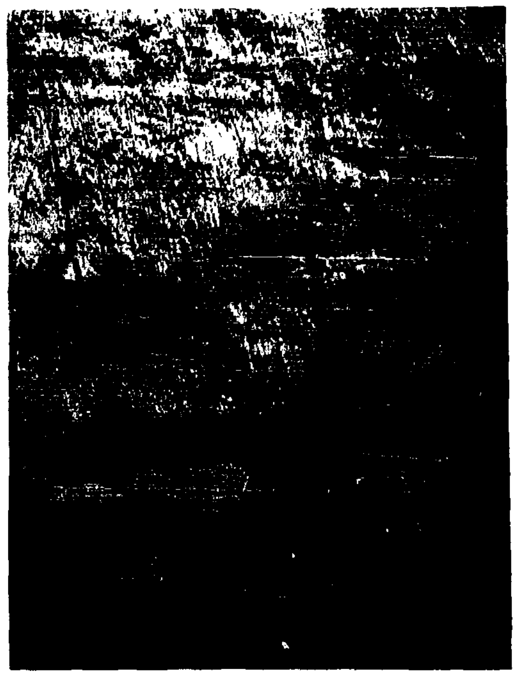


3a SURFACE MACHINED

3b SURFACE MACHINED, 0.008" REMOVED BY ELECTROPOLISHING



3c SURFACE MACHINED, 0.011" REMOVED BY ELECTROPOLISHING



3d SURFACE MACHINED, 0.023" REMOVED BY ELECTROPOLISHING

FIG. 3 SURFACE OF TUNGSTEN SPECIMENS TESTED IN 3 POINT BENDING MAGNIFICATION x250

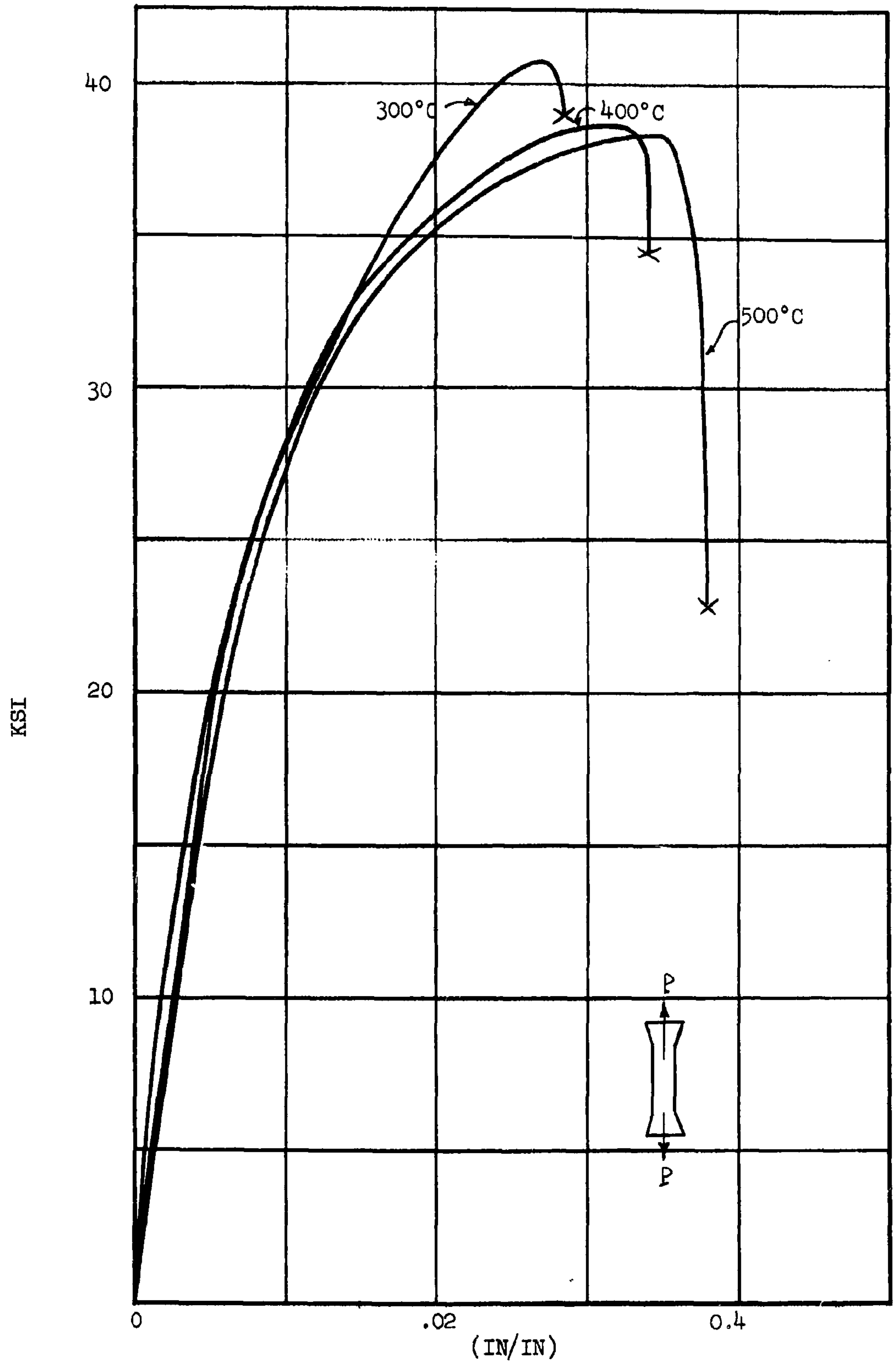


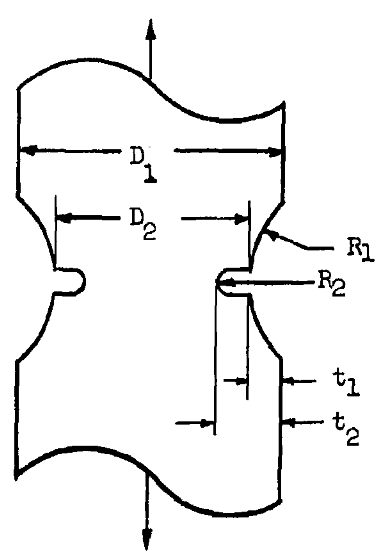
FIG. 4 STRESS ELONGATION CURVE FOR RECRYSTALLIZED ELECTROPOLISHED TUNGSTEN AT 300°C, 400°C and 500°C.

TABLE I

DOUBLE NOTCHED BRITTLE TITANIUM RESULTS

SPEC. NO.	K_t BASED ON LARGE RAD	K_t BASED ON SMALL RAD	K_t* BASED ON VAR D_2 AND SMALL RAD	σ_N KSI	DEPTH LARGER t_1	DEPTH SMALLER t_2	RADII LARGE R_1	RADII SMALL R_2
B1	1.62	7.72	2.6	187.5	.375	.750	.500	.0625
B3	1.68	7.72	2.66	185.5	.281	.750	.500	.0625
B5	1.69	7.72	2.70	184.4	.1875	.750	.500	.0625
B7	1.63	7.72	2.72	178.9	.0937	.750	.500	.0625
A2	2.62	7.72	2.75	184.8	.250	.750	.125	.0625
A4	2.02	7.72	2.75	185.3	.250	.750	.250	.0625
A5	1.69	7.72	2.75	186.4	.250	.750	.500	.0625
A8	1.40	7.72	2.75	187.2	.250	.750	1.000	.0625

*NOTE K_t CALCULATED USING R_2, $(t_2 - t_1)$ AND D_2



SPECIMEN CONFIGURATION

DISTRIBUTION LIST- CONTRACT N600 (19)-59514

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